Multiple Antenna Wireless An Overview

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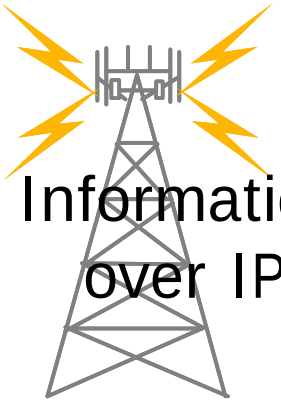
NIST, MRA Workshop
October 6, 2005

Outline

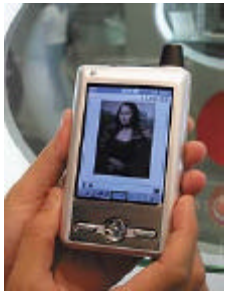
- Introduction, markets
- Multiple antennas basics
- Performance value
- Practice – standards, trends
- Summary

Mobile Internet Delivery

Broadband Multimedia Information / Entertainment over IP



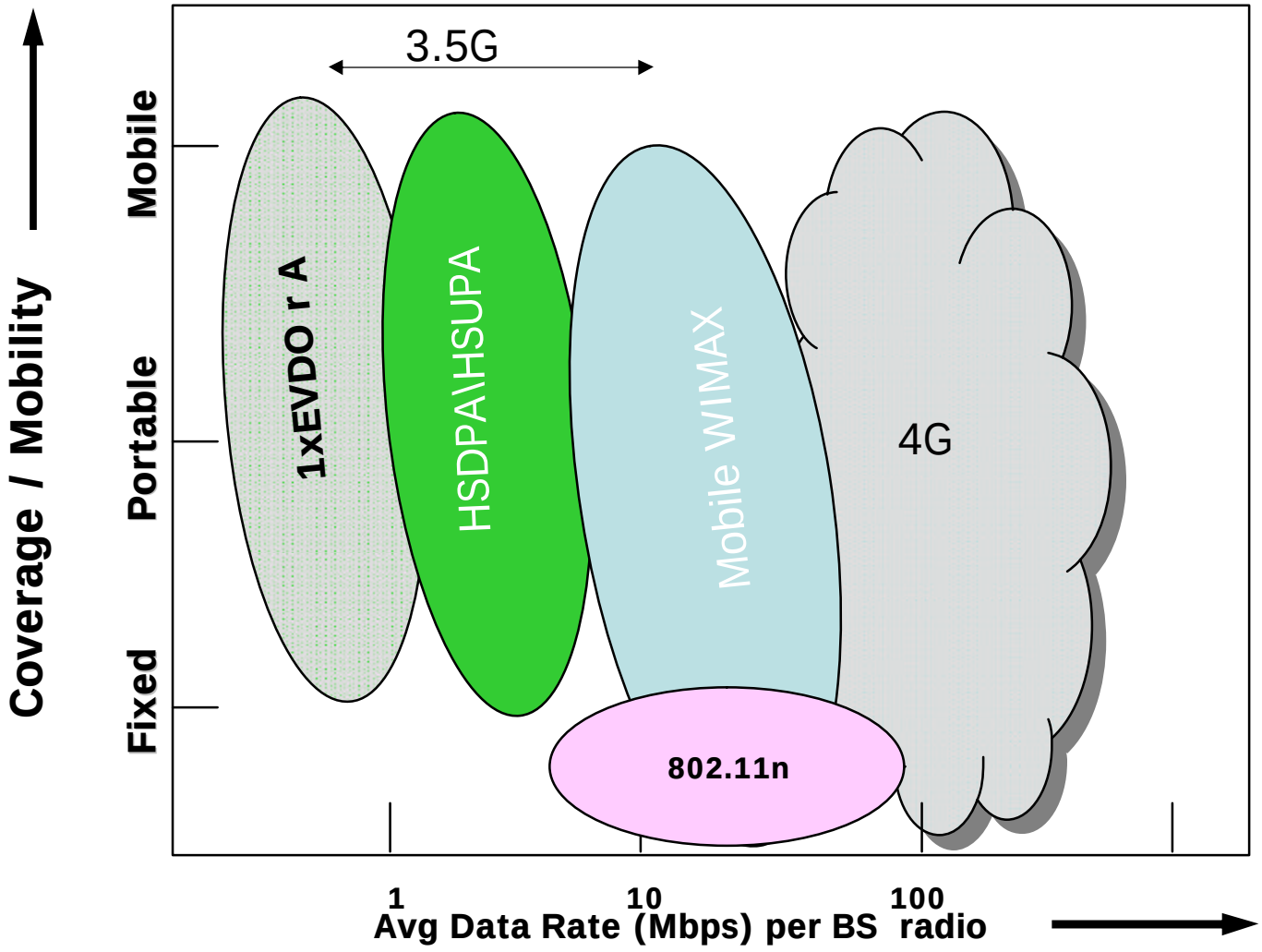
Portable terminal



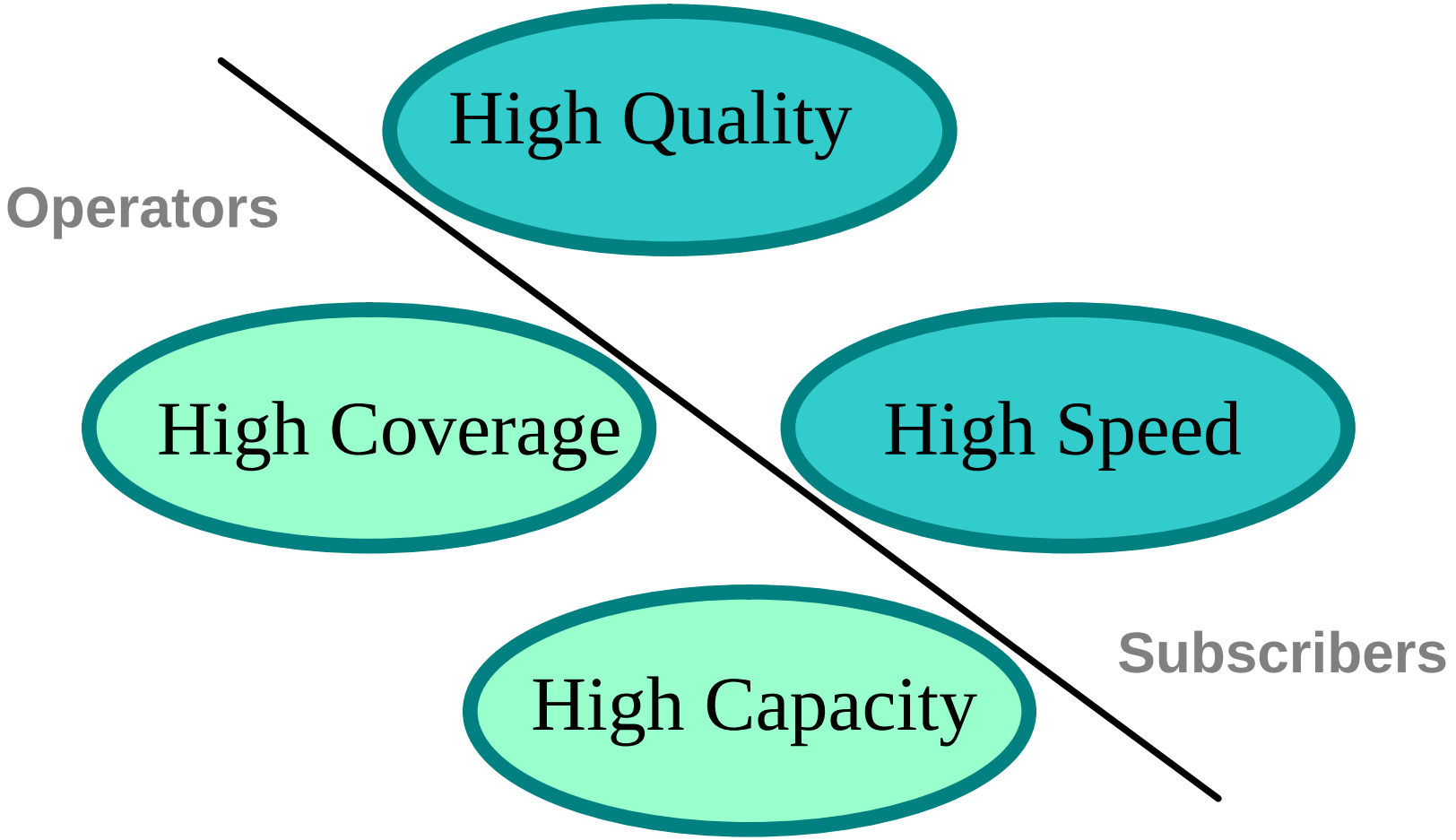
Mobile terminals

Consumer Devices

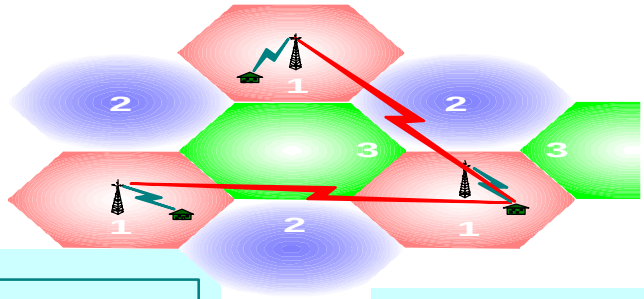
Wireless Internet Standards

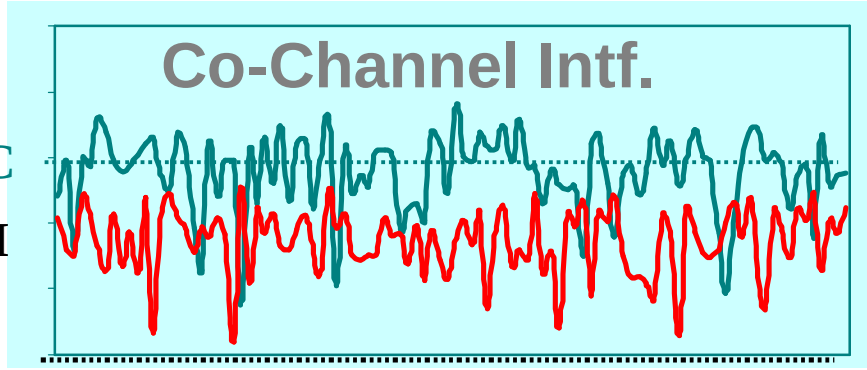


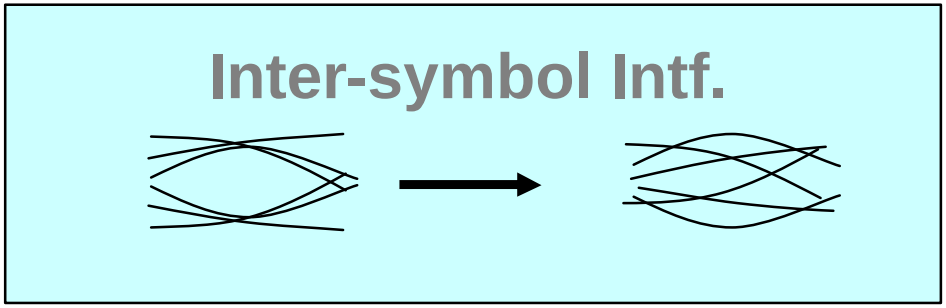
Principal Challenges in Wireless Transmission



Channel Impairments







Carrier Requirements

- Aggregate Avg. throughput per BS > 10 Mbps
- Sustained throughput per SS > 1 Mbps
- High Spectrum Eff. > 7.5 bps/Hz/Cell
- Delay < 50 ms
- Flexible channelization & band plans to suit regional needs
- Multimedia services delivered over IP v4, v6
- Mobility (capacity may degrade > 60 Kmph)
- All IP core network architecture
- Low power terminals - Joules / Mbyte
- Low cost - $ / Mbps / Sq. Km

Baseline Features for 3.5G

- Cellular 1x1 (full) frequency reuse
- Closed loop transmit channel state information (Tx-CSI)
- Fast HARQ, fast link adaptation, fast BS switching
- High order QAM, Soft handoff on UL
- Interference averaging

Evolutionary Features 3.5G

- Multiple access - OFDMA
- Wideband 10/20 MHz
- MIMO: single user and multi-user
- Opportunistic scheduling in time, frequency and space
- Interference avoidance/ cancellation

3.5G Technologies

	DO Rel A	HSDPA	WiMax (802.16(e))
DL peak data rate Bandwidth	3.07 Mbps 1.25 MHz	14.4 Mbps 5 MHz	70 Mbps 20 MHz
UL peak data rate	1.8 Mbps	2 Mbps	20 Mbps
IP termination	RNC/PDSN	RNC/PDSN	BTS
Bandwidth efficiency features	- CDMA + Low latency - IP at RNC**	- CDMA + PHY HARQ - IP at RNC**	+ OFDM - MAC HARQ* + IP at BTS
Standards compatibility	Yes	Yes	Yes
Deployment	2005	2005	2005
Duplexing	FDD	FDD	TDD / FDD
BB complexity (incl. memory)	~1.2 million gates	~ 1 million gates	~ 2.5 million gates

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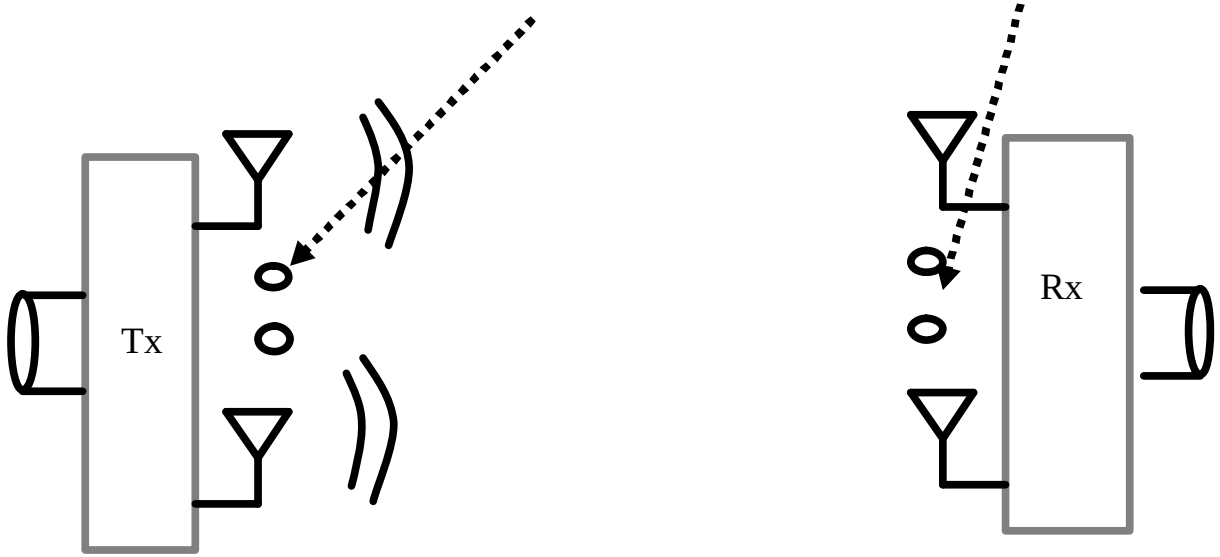
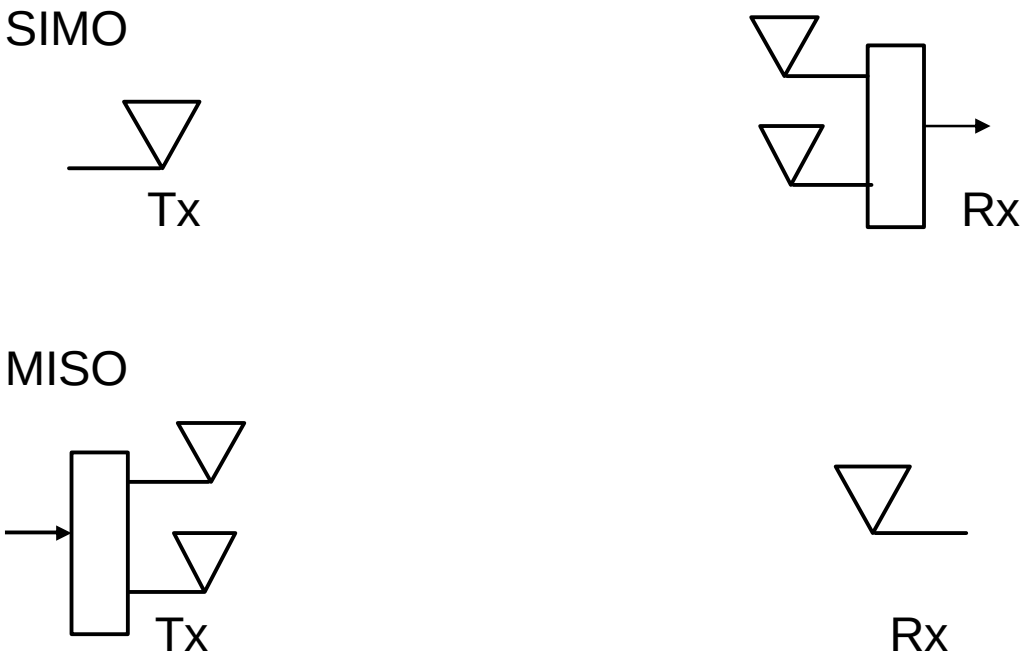
MIMO - A Breakthrough

Multiple Input - Multiple Output



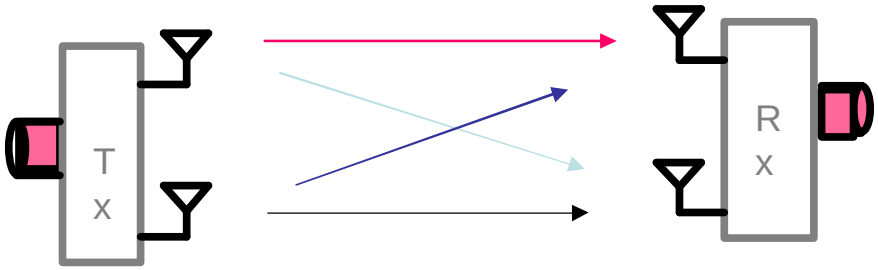
Originally proposed - Paulraj / Kailath 1994
Rediscovered and Thy Dev. – Foschini,.. 1997

SIMO and MISO

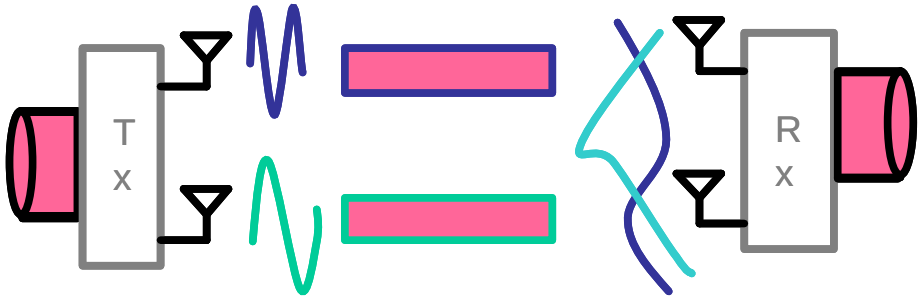


SIMO used for many years, MISO in 3G, MIMO in 3.5G ++

Leverages of MIMO



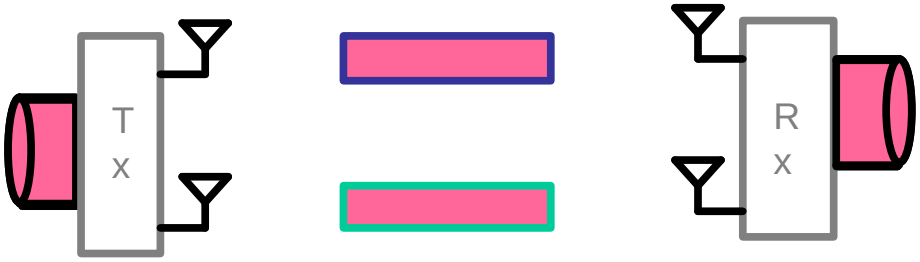
Diversity: Increased Diversity (also in MISO, SIMO)



Spatial Multiplexing: **Increased rate** (only MIMO)

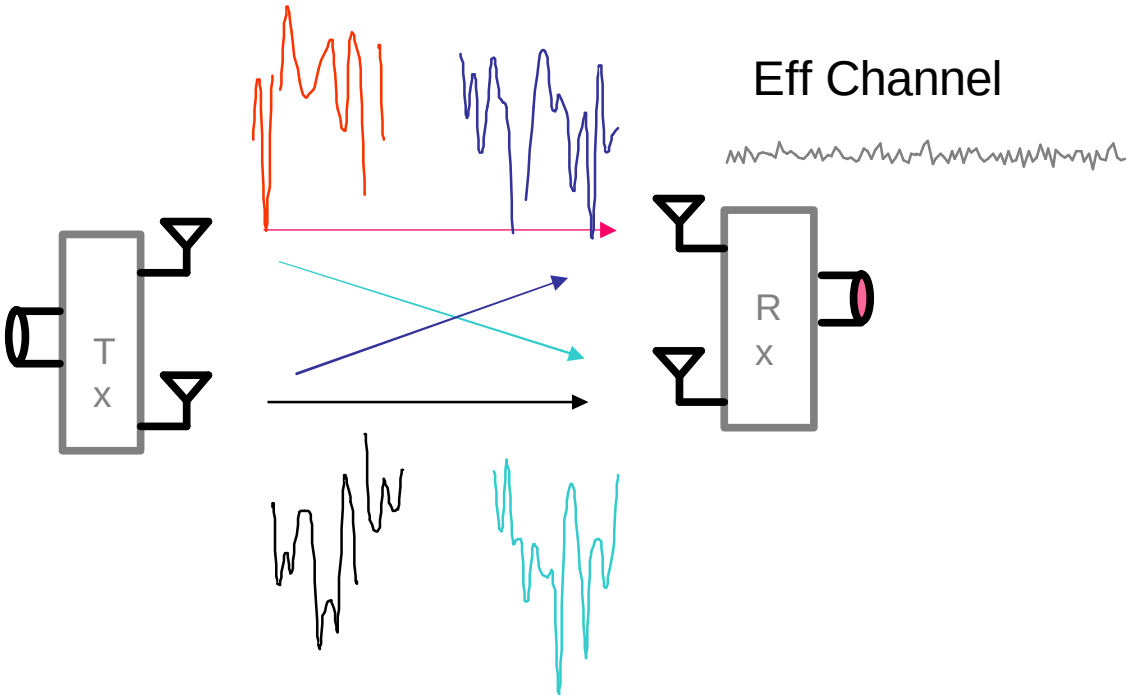
Exploits scattering to create multiple spatial channels

Spatial Multiplexing (SM)



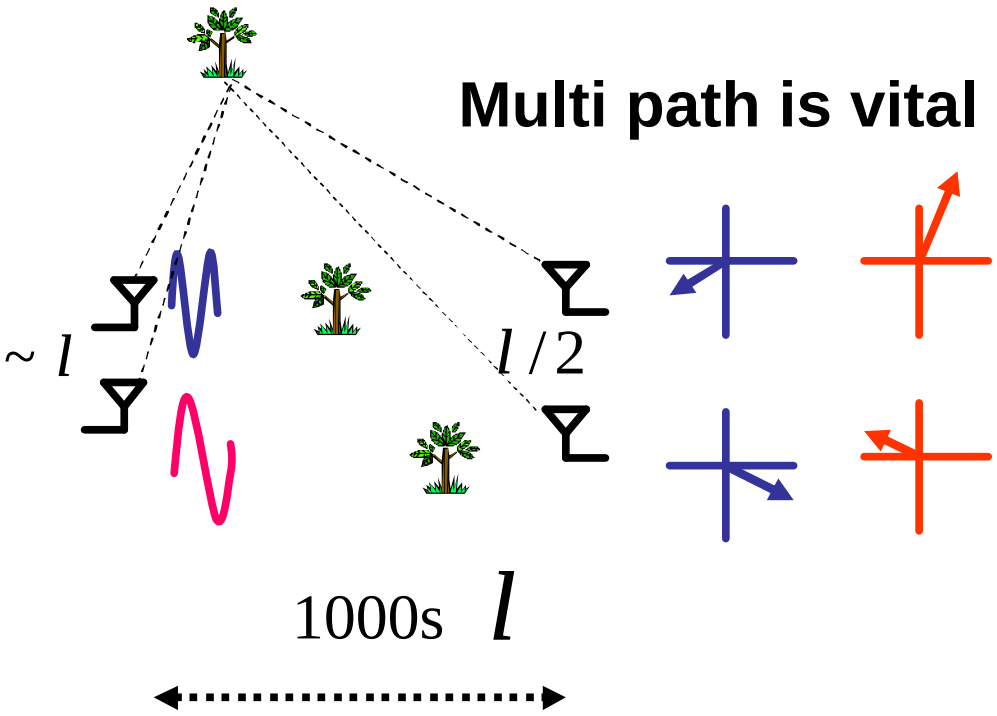
SM increases throughput by creating multiple parallel channels. Number of channels = Min of Tx or Rx antennas

Diversity



The 4 independently fading channels are combined to generate an effective channel with reduced fading

Spatial Multiplexing



Capacity of MIMO Channel

Channel known to Rx, unknown to Tx

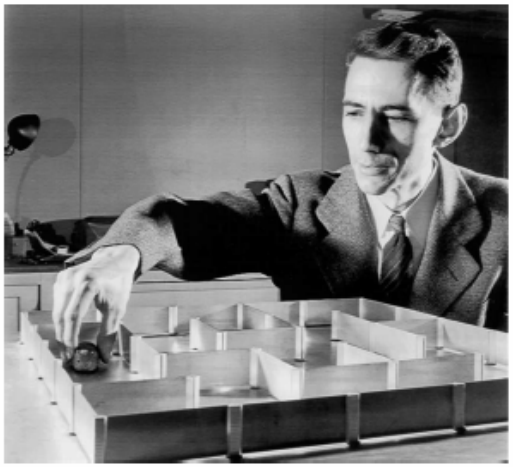
$$C = \log_2 \det\left(I + \frac{r}{M} HH^* \right)$$

r is the received SNR

M is the number of transmit antenn

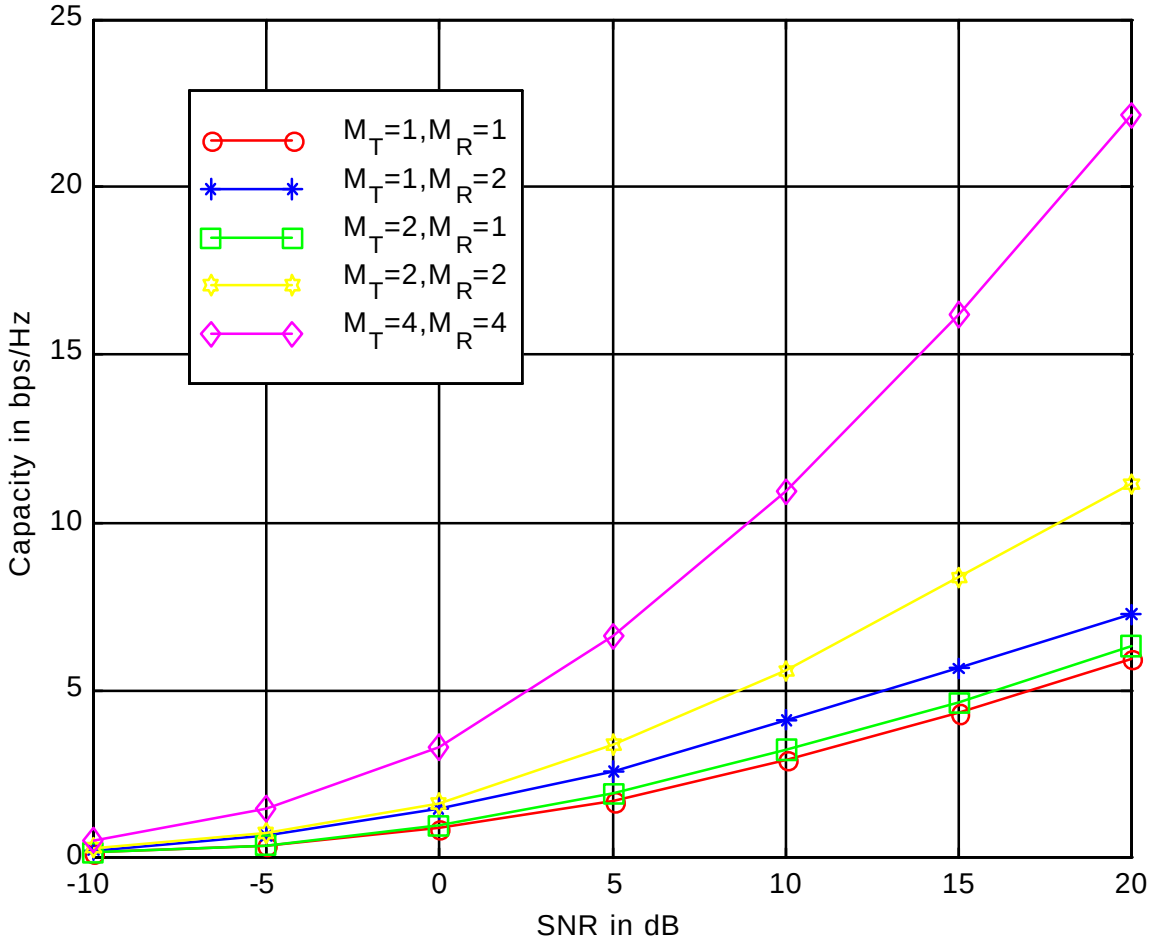
H is the channel transfer function

Teletar (1997), Foschini,...



Claude E. Shannon (1916-2001)

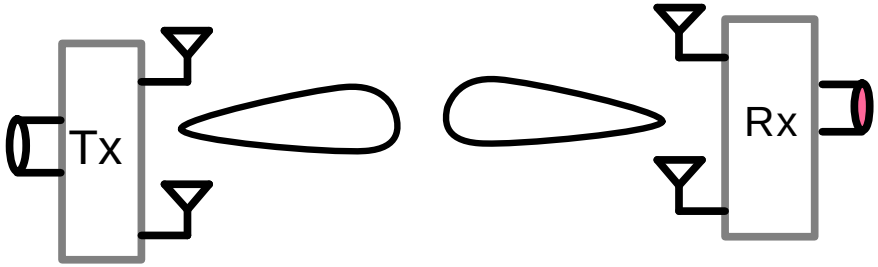
Ergodic Capacity



Exploiting 2 x 2 MIMO

	Rate 1 Single Stream (one symbol out per symbol period on average)	Rate 2 Two streams (two symbols out per symbol period on average)
Tx knows channel (Full Tx-CSI)	Single conjugate beam pair at Tx and Rx	Multiple conjugate beam pairs at Tx and Rx, one pair per stream
Tx does not know channel (No Tx-CSI)	ST coded Txn.	ST Coded Txn.

Rate 1 with Tx-CSI



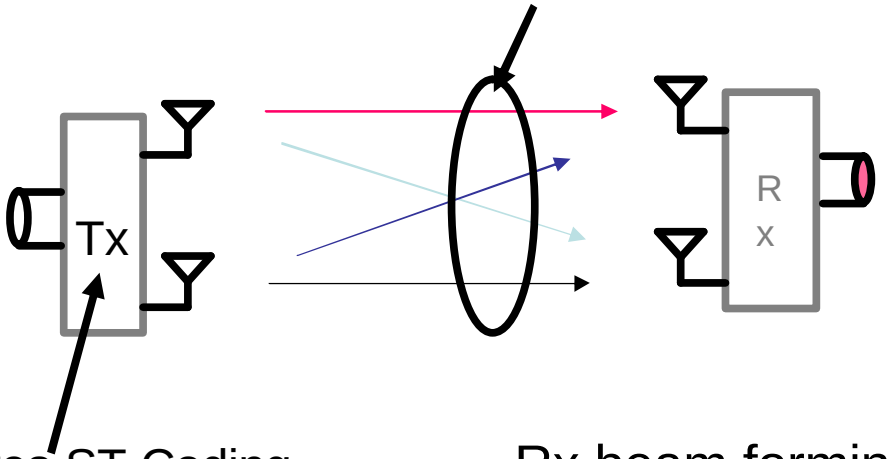
Tx-CSI enable Tx beam forming

Rx beam forming with Rx CSI

Rate 1 (eigen) beam forming captures diversity and improves rate

Rate 1 w/out Tx-CSI

Signal routed through all the four independently fading links

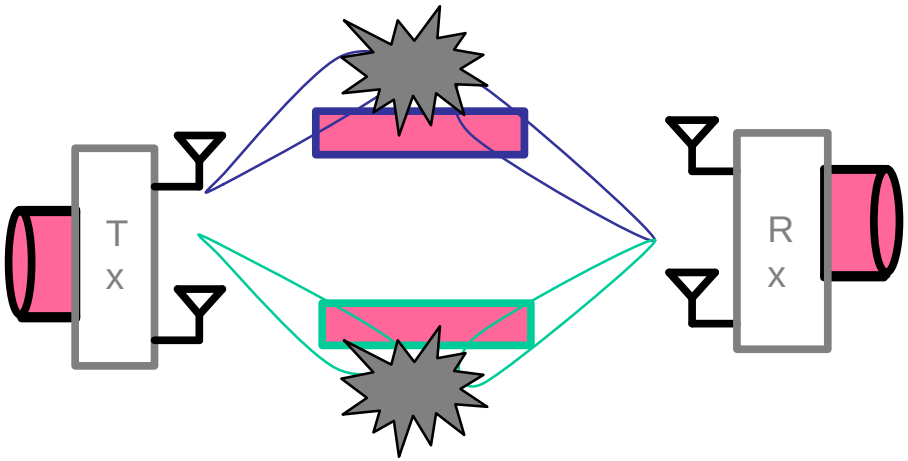


Requires ST Coding

Rx beam forming with Rx CSI

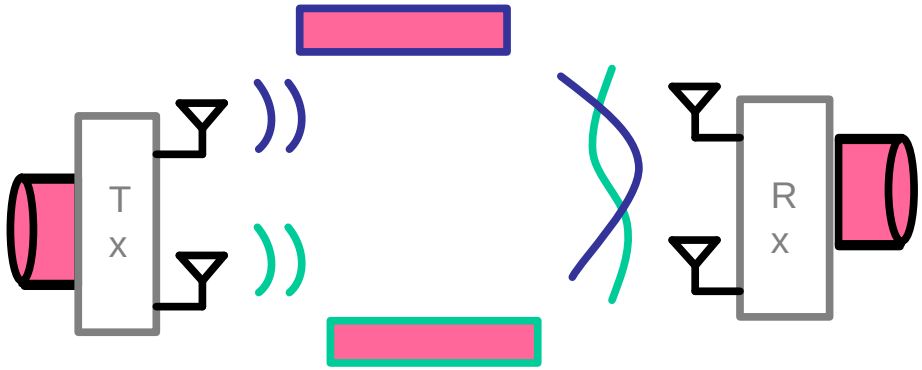
Space-Time Coding captures diversity in the channel
Small improvement in rate

Rate 2 / Spatial Multiplexing with Tx-CSI



With Tx CSI, SM reduces to multi beam forming.

Spatial Multiplexing w/o Tx-CSI

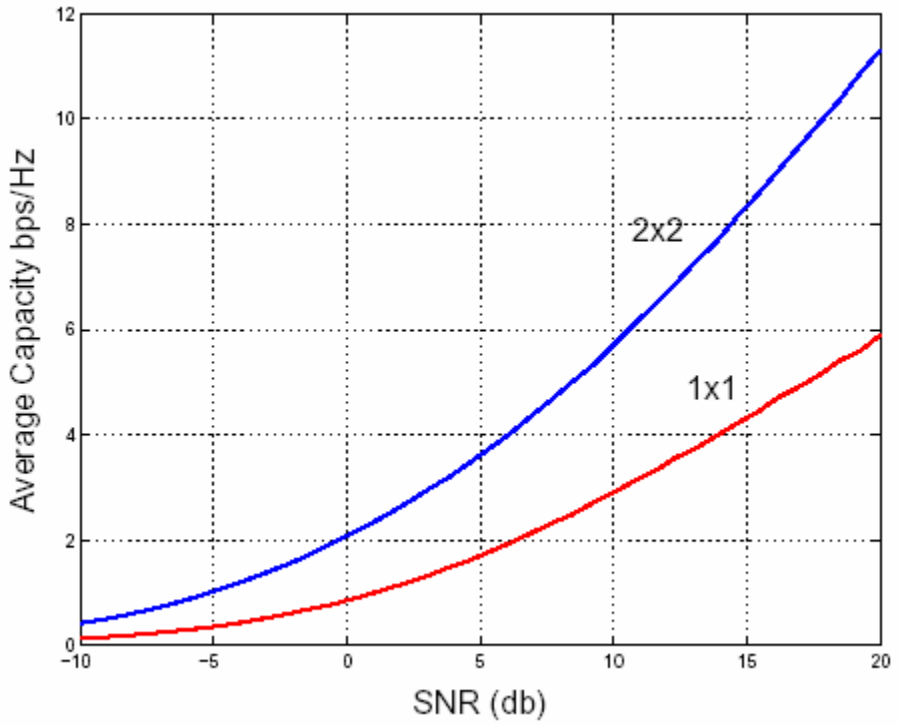


Without channel knowledge at Tx: SM implies transmitting two independent streams at each antenna. Rx unscrambles streams

MIMO Capacity with Tx-CSI

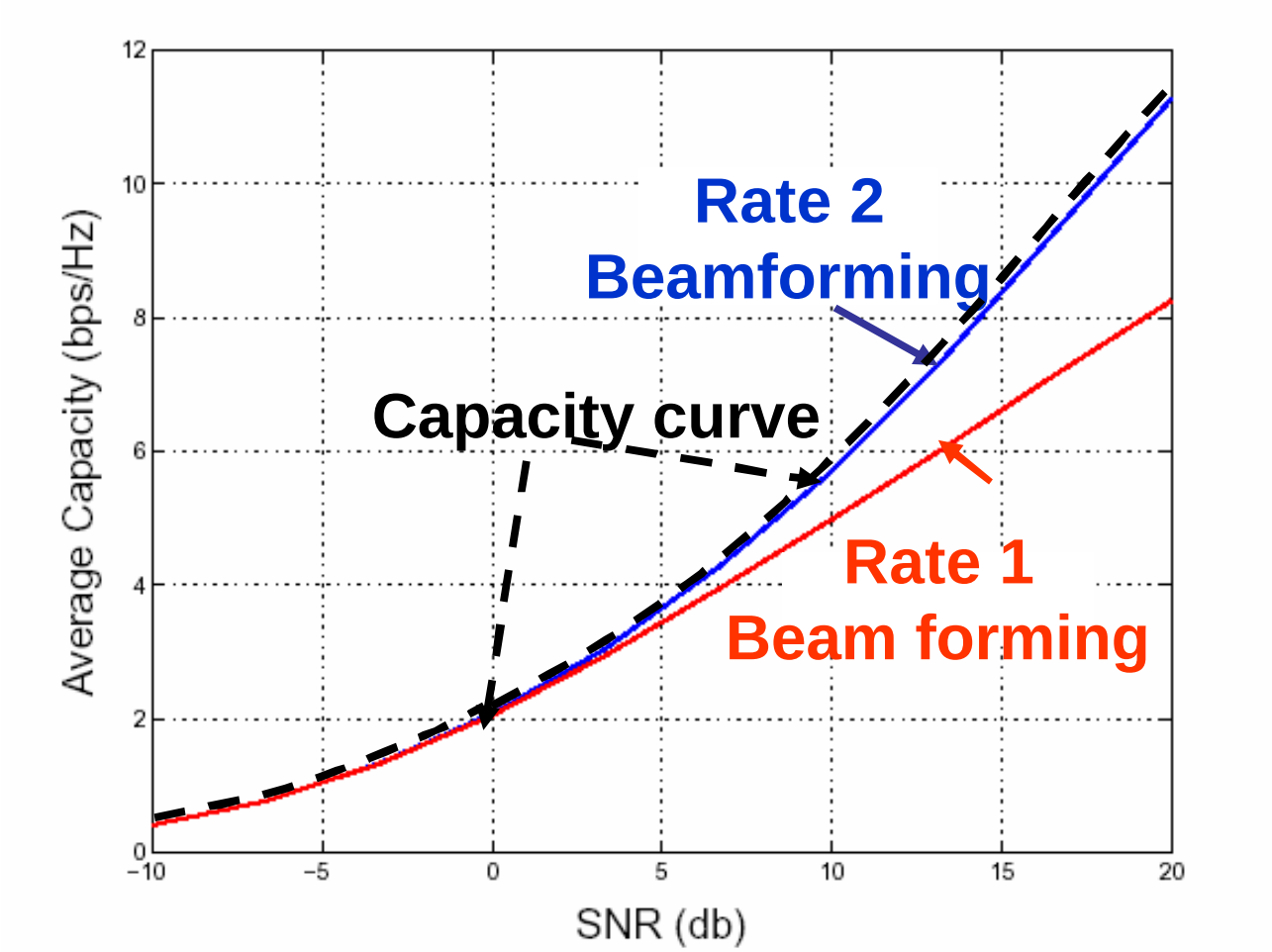
Perfect Tx-CSI

Single User



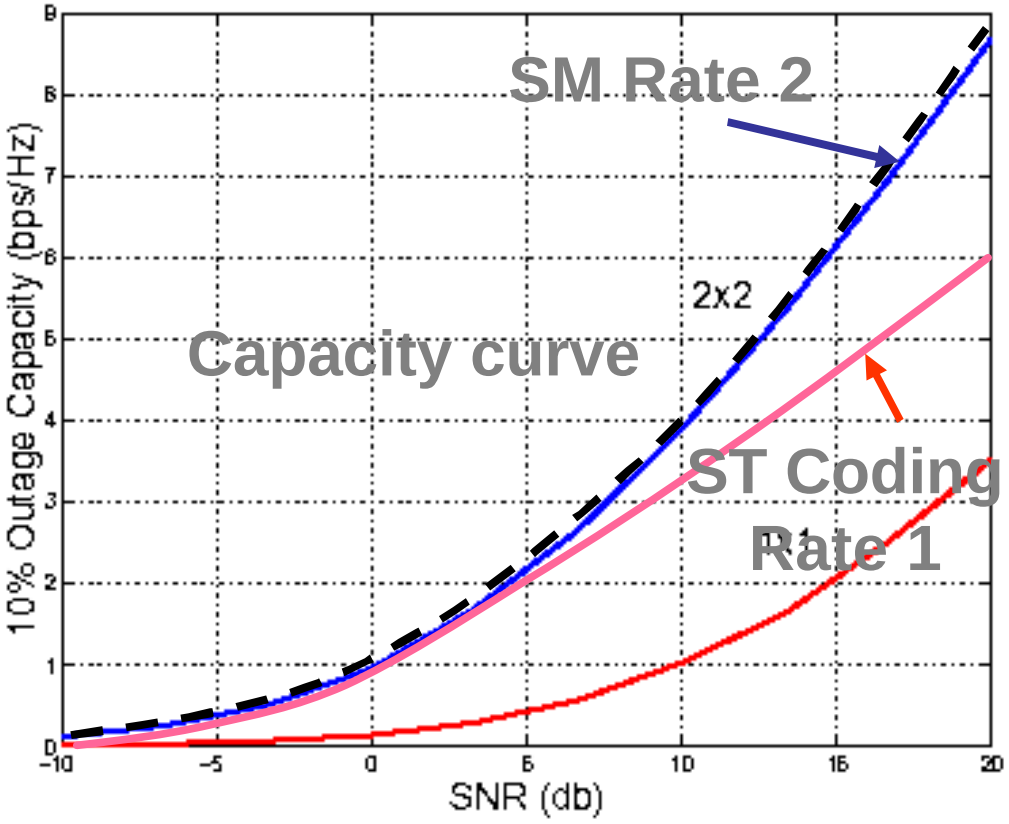
$$\text{Average Capacity} \approx O\left(M \log_2(\text{SNR})\right)$$

Transmission with Tx-CSI



Rate 1 beam forming is near optimal for SNRs below 3 dB,
Rate 2 beam forming is needed above 3 dB

Transmission w/o Tx-CSI



Rate 1 ST Coding is optimal for SNRs below 3 dB,
Rate 2 SM is needed to reach optimality above 3 dB

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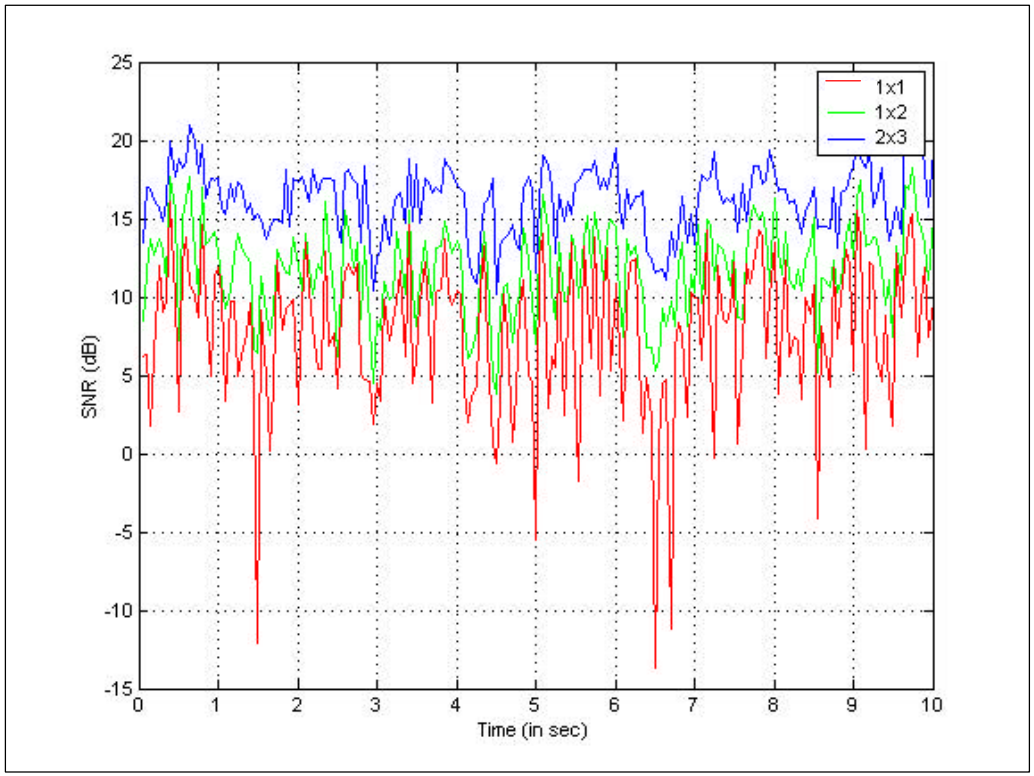
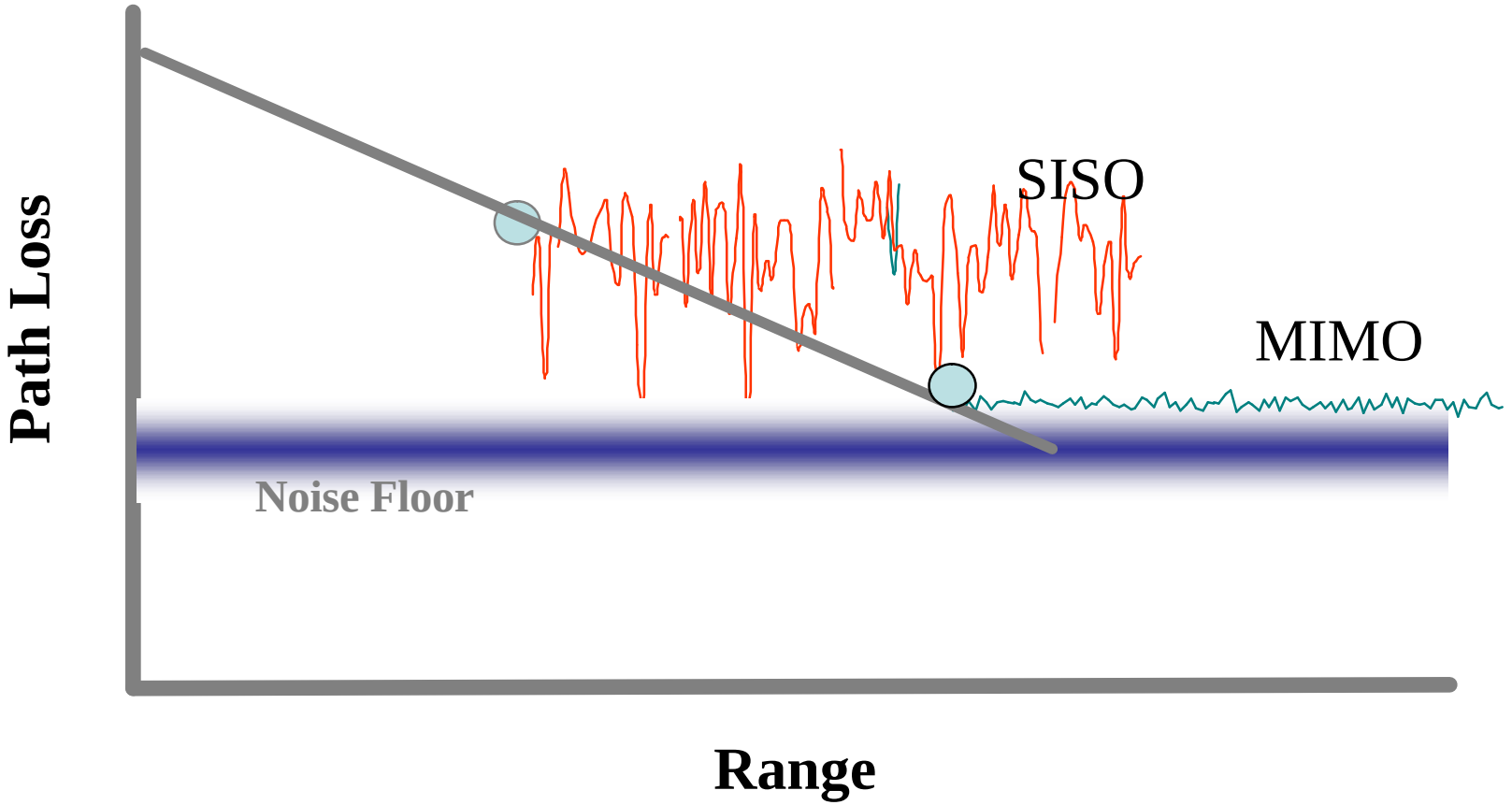
MIMO : Diversity

Stanford University Test Bed May 2000



Antenna diversity reduces signal fluctuation and can also raise signal avg power

Diversity and Beam forming: Better Range

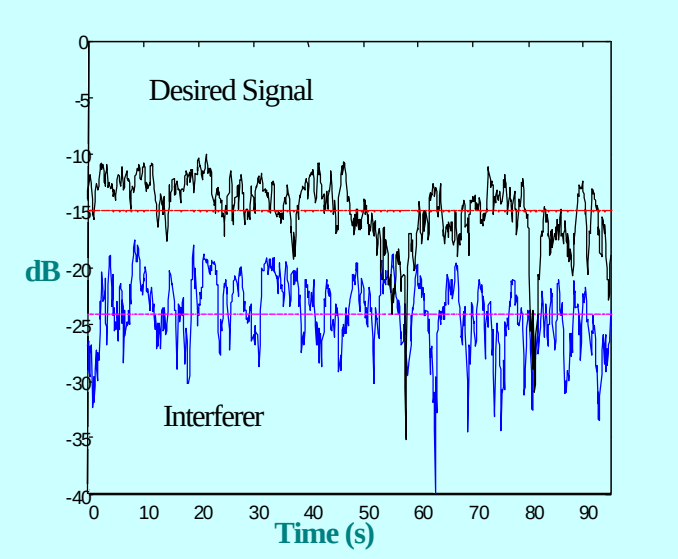


Diversity allows higher path loss – better range

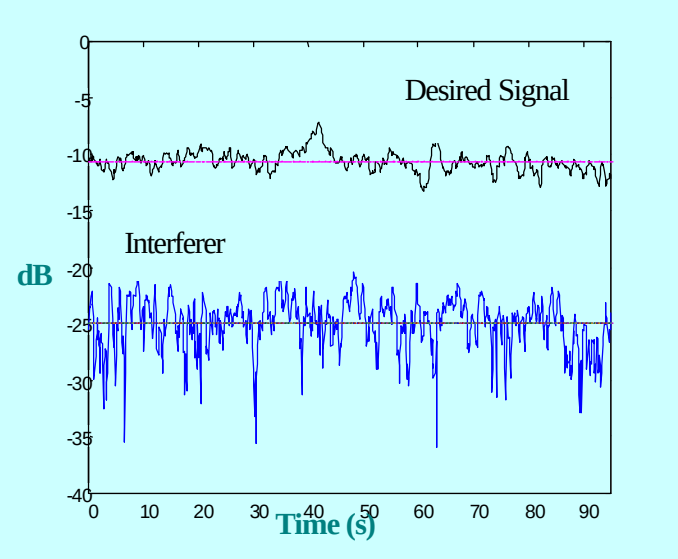
MIMO: Interference Mitigation

Stanford Univ. Test Bed, May 2000

SISO

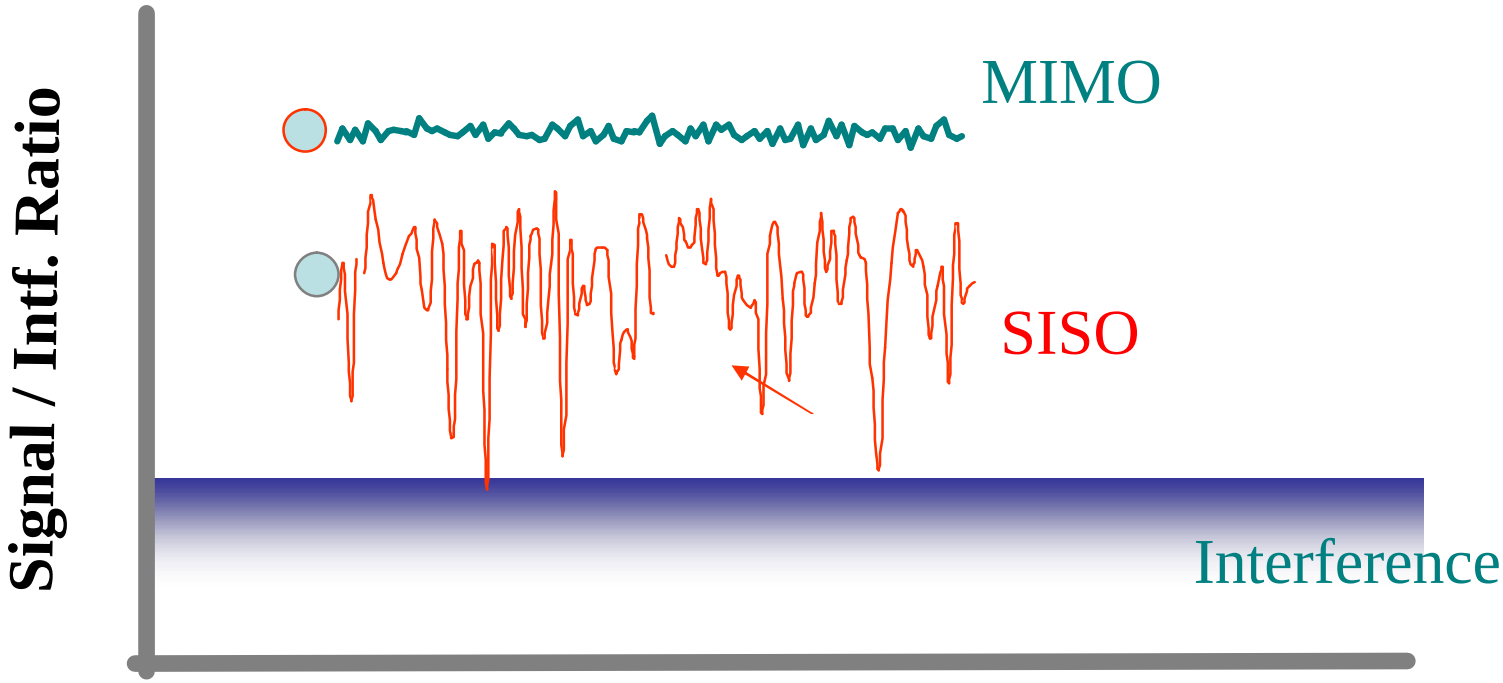


MIMO

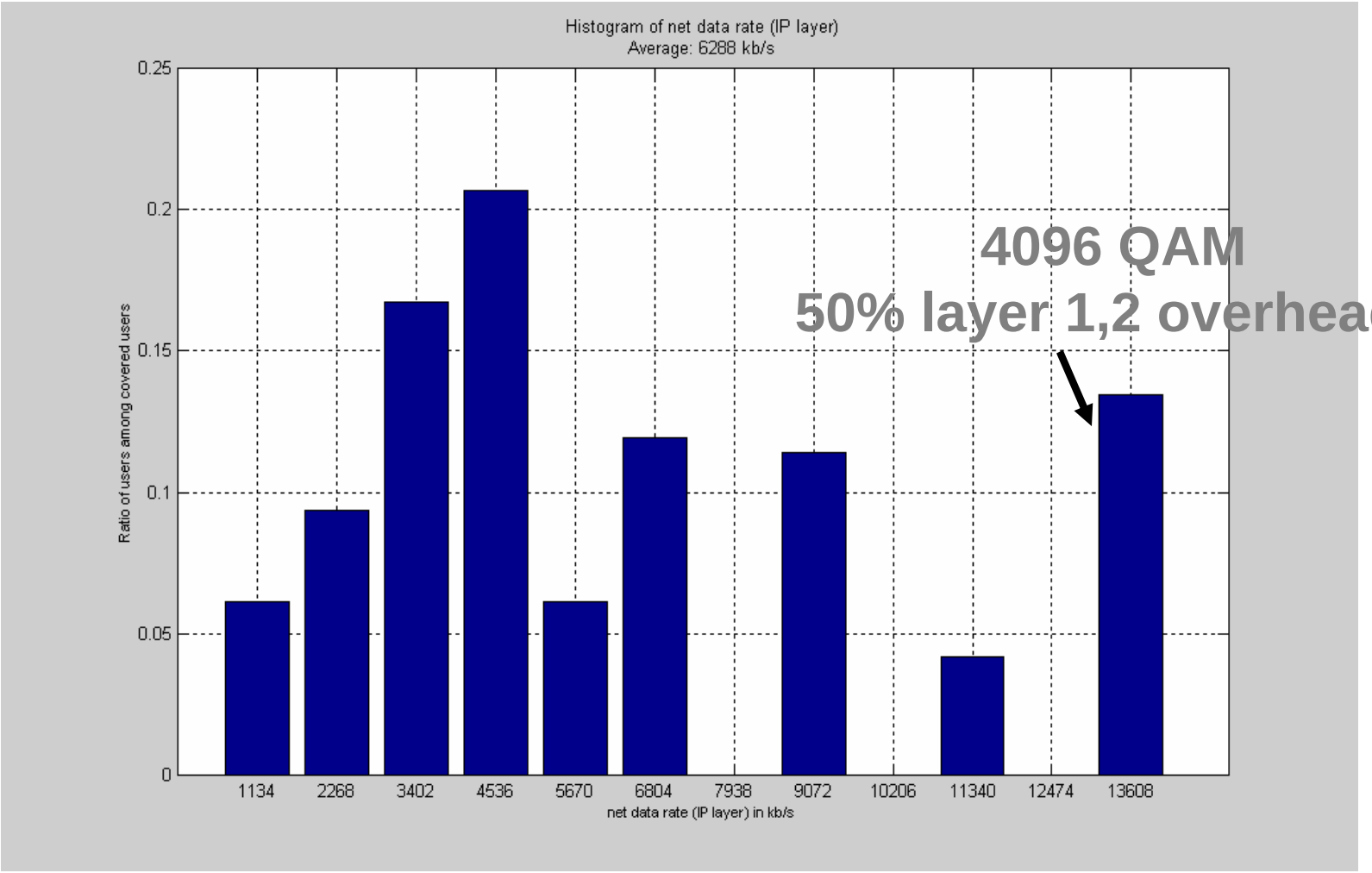


Diversity also reduces interference – better throughput

Diversity Enables Better Reuse



Higher Data Rates with Spatial Multiplexing



2 MHz channel, Iospan Wireless, San Jose Test Bed, Range 3.12 Miles, May 2002

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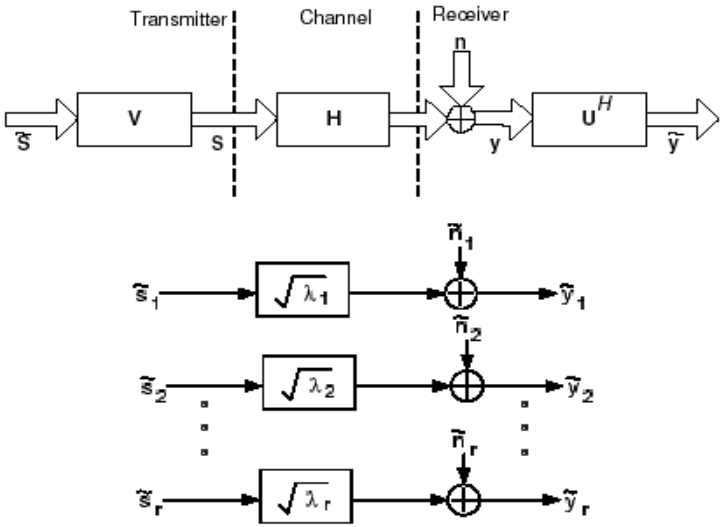
Advanced topics

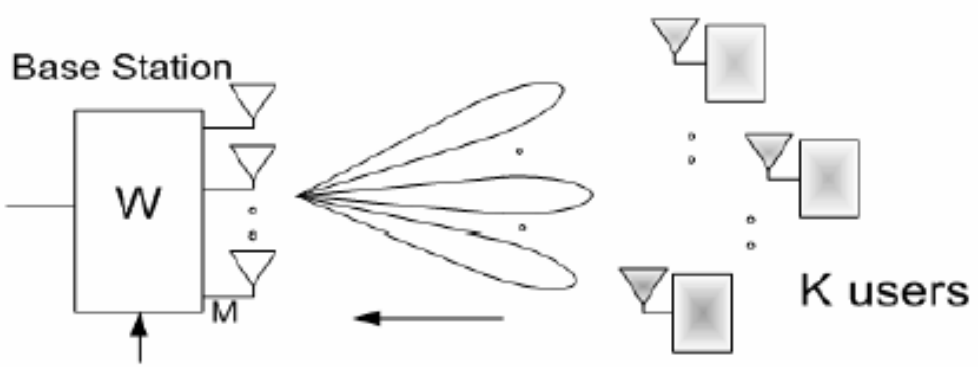
- Capacity of ST channels
- ST channels and modeling
- ST coding
- ST receivers
- Exploiting channel (full or partial) at Tx knowledge
- Cross layer design

ST- Coding with Tx-CSI



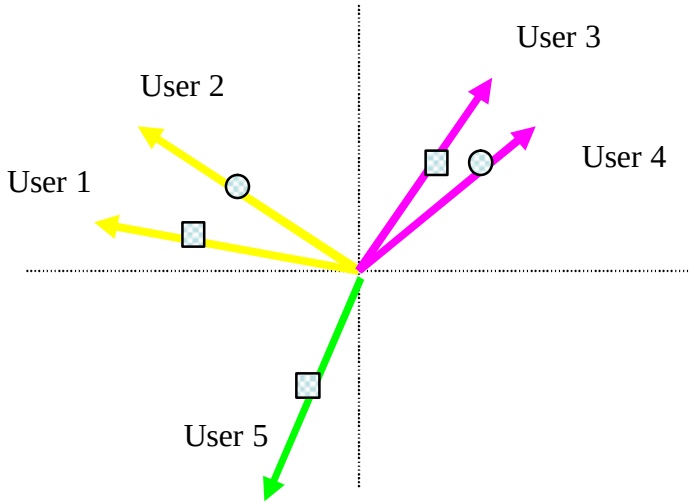
- Decomposes into parallel SISO modes
- SISO Coding
- Per mode rate Control
- Low Rx Complexity

Cooperative MIMO - SDMA

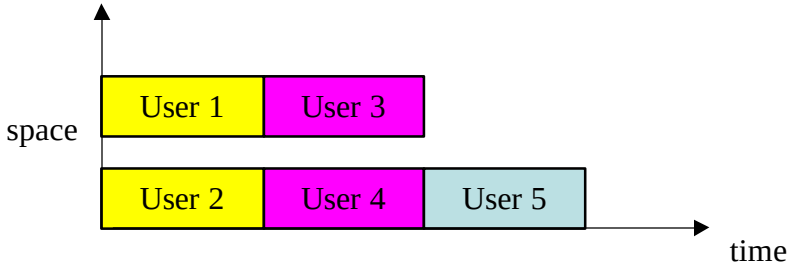


Base station transmits to / receives from multiple users
Possible when spatial signatures are near orthogonal

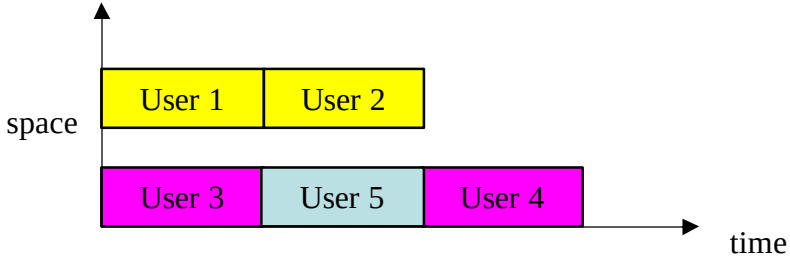
Cooperative MIMO



Spatial signatures

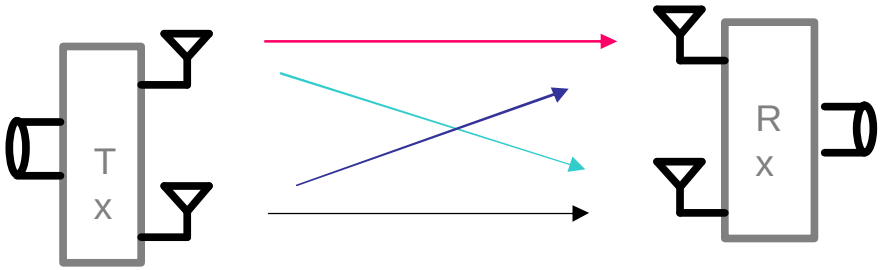


random assignment



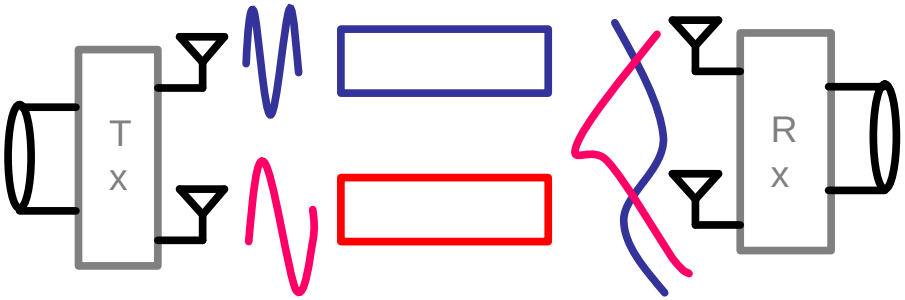
channel-aware assignment

Diversity Coding



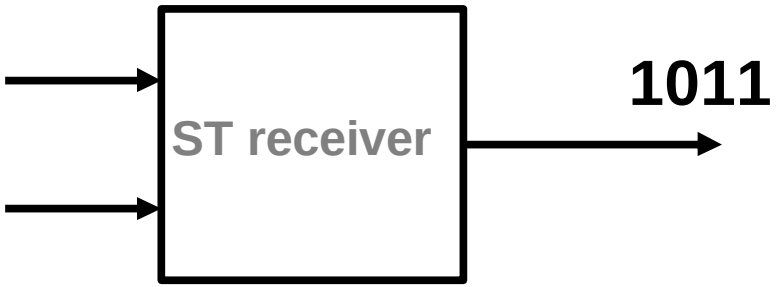
- **Orthogonal ST Block Codes : Alamouti (1998) M=2, Tarokh (2001) M > 2, Lindskog-Paulraj (2000) delay spread channels, rotation-interleaving codes**
- **ST Trellis Codes Tarokh, Seshadri**

SM Coding



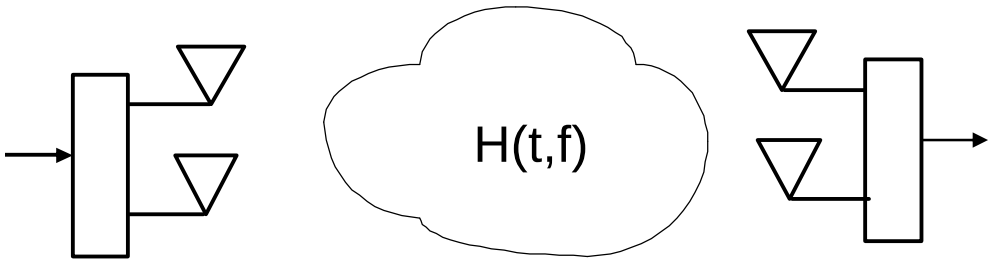
- **Horizontal, Vertical and Diagonal coding (BLAST) Foschini (1998), Threaded codes (2001) El Gamal-Hammons**
- **Dispersion codes Hocwald-Hassibi, Heath-Paulraj**
- **Turbo coding – Selvathurai-Haykin, ten Brink, Arivayastkul, ..**

ST Receivers



- **ST receiver: Balancing BER/diversity with complexity**
- **Optimal ML schemes not practical at high QAM and antennas**
- **Simpler schemes: Ordered successive cancellation (V-BLAST) Foschini**
- **Sphere decoding**

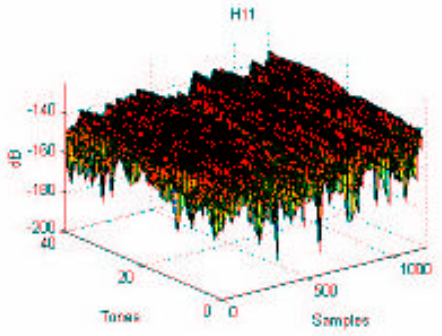
MIMO Channel Models

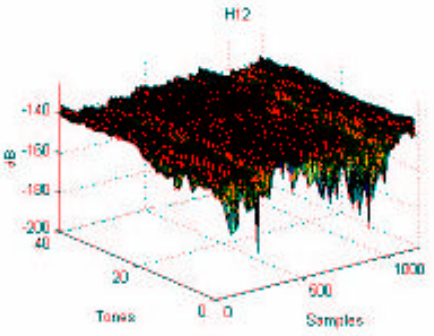


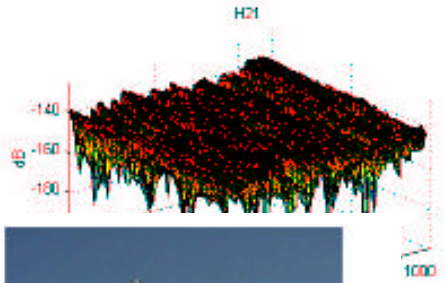
- Models are needed to predict performance
- Analytical Models useful for simulations
- Physical Models: useful to understand observed data

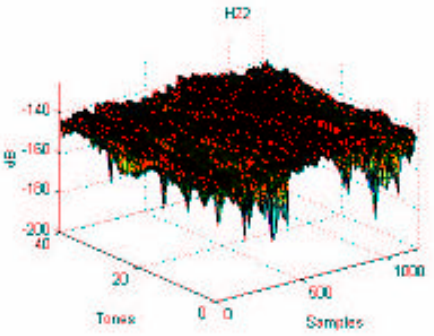
MIMO Channel Measurements

Stanford (Fixed)
Lucent (Mobile, indoor)
CPK, Phillips,…



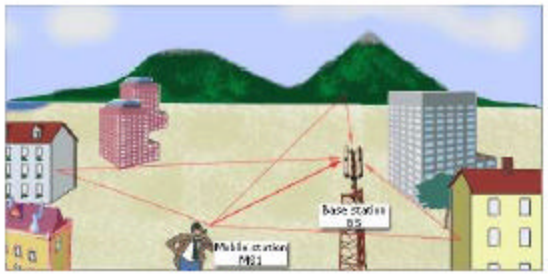


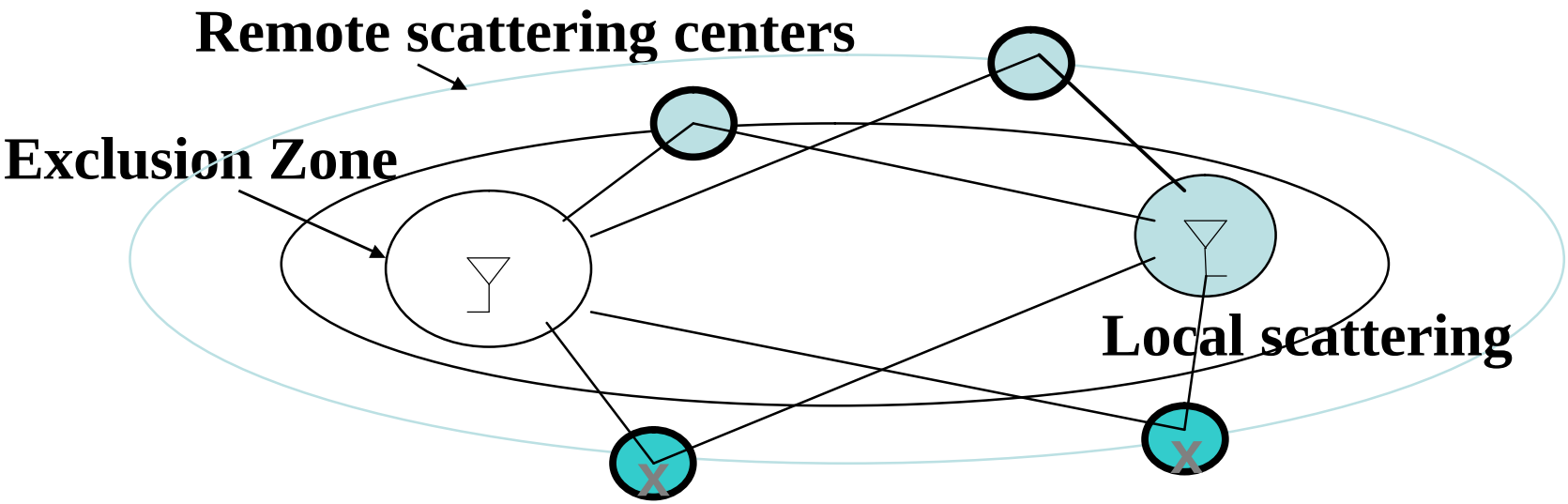




Physical Models

Useful to predict channel behavior in particular scenarios





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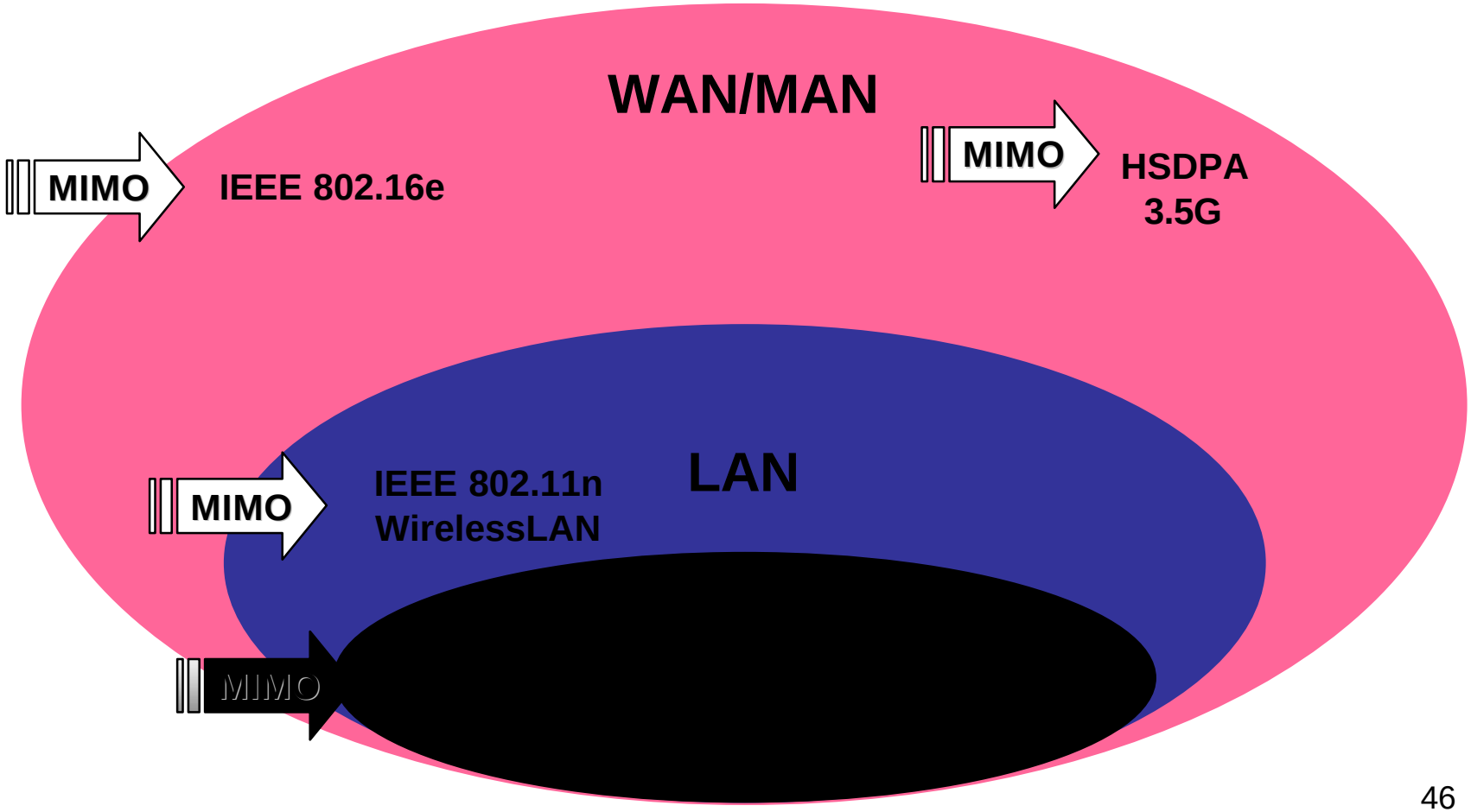
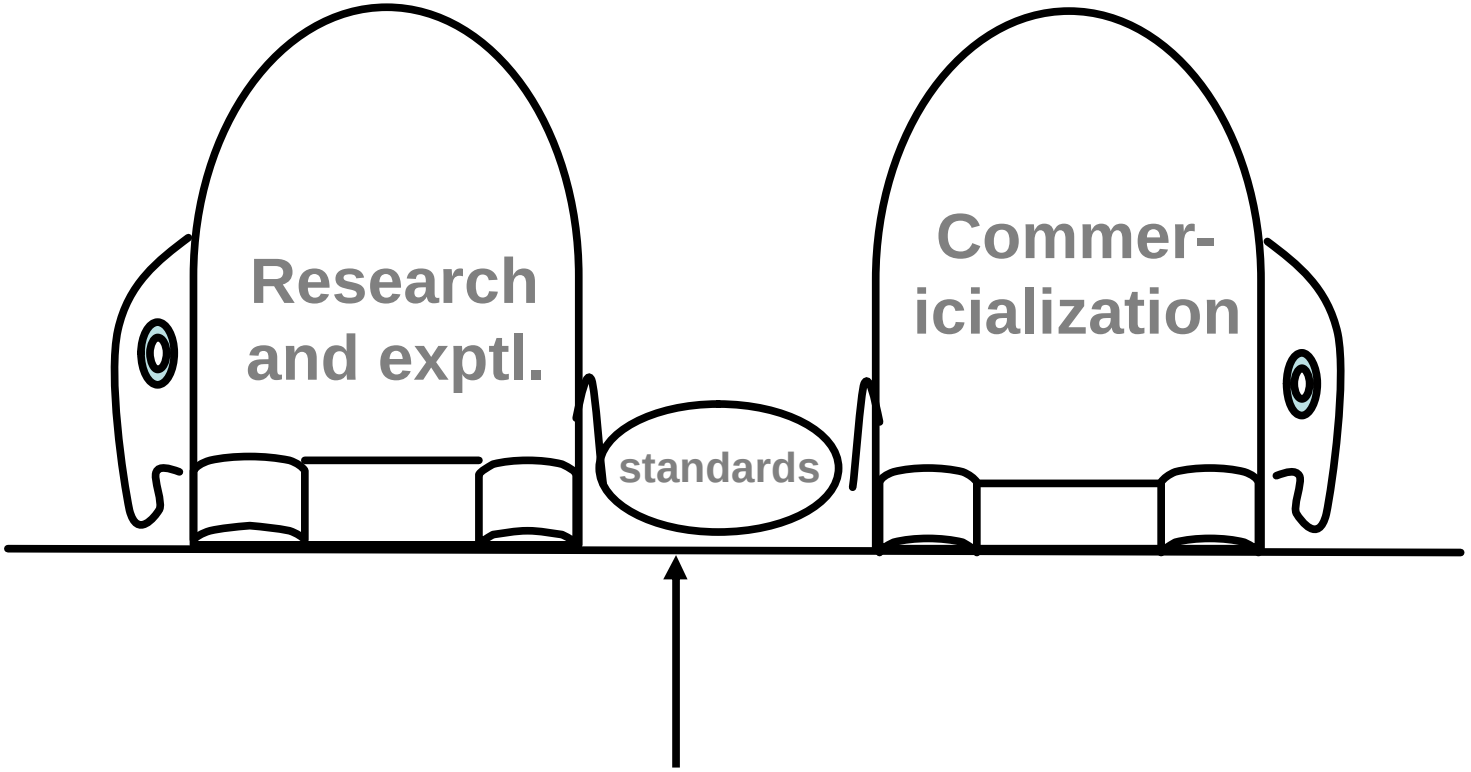
Global Wireless Standards



Two Elephants



IEEE 802.16e

- 4x2 MIMO in DL
  - STC zone Rate 1,2 (no Tx-CSI)
  - Beam forming zone Rate 1,2 (good Tx-CSI)
  - STC Pre coding Rate 1,2 (with partial Tx-CSI)
- 2x4 MIMO in UL
  - PUSC and B-AMC zones Rate 1,2 (good Tx-CSI)

IEEE 802.11n WiFi

- 4x4 MIMO supported in DL
  - Rate 1,2 in STC mode
- TGnSync and WWiSE consortiums being merged

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- Summary

In Conclusion

- Multiple antenna (MIMO) technology now widely recognized as a fundamental leverage for improving price/performance
- Good understanding available to build robust systems
- MIMO being inserted into 802.11n, 802.16e, 3.5G proposals, 4G,..